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Turbulence-induced noise of a submerged cylinder using a permeable FW−H method

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Abstract

Among underwater noise sources around submerged bodies, turbulence-induced noise has not been well investigated because of the difficulty of predicting it. In computational aeroacoustics, a number of studies has been conducted using the Ffowcs Williams−Hawkings (FW−H) acoustic analogy without consideration of quadrupole source term due to the unacceptable calculation cost. In this paper, turbulence-induced noise is predicted, including that due to quadrupole sources, using a large eddy simulation (LES) turbulence model and a developed formulation of permeable FW−H method with an open source computational fluid dynamics (CFD) tool-kit. Noise around a circular cylinder is examined and the results of using the acoustic analogy method with and without quadrupole noise are compared, i.e. the FW−H method without quadrupole noise versus the permeable FW−H method that includes quadrupole sources. The usability of the permeable FW−H method for the prediction of turbulence-noise around submerged bodies is shown.

Keywords: Turbulence-induced noise; Circular cylinder; Acoustic analogy; Permeable FW−H method; OpenFOAM

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1. Introduction

Future ships will be faster, bigger and more complex while satisfying ever-increasing demands for better acoustic performance. Accordingly, future hydrodynamic designs for ship hulls and appendages or other submerged bodies will have to meet higher acoustic requirements. Studies on hydrodynamic noise generated by such bodies have been mainly concentrated on the subject of the propeller and the propagation of sound, and have demonstrated limited understandings and predictability. However, noise generated by other underwater appendages underwater will increase as they become faster and larger. For appendages like a sonar dome, to maintain the performance so that it is not affected by its self-noise, it is important to be able to predict noise generated by vortex shedding, which involves non-linear quadrupole source noise. By correctly predicting such turbulence-induced noise, a designer can deal with the characteristics of flow noise at the design stage.

Objects in motion disturb the surrounding fluid to produce hydrodynamic noise. Such noise can be predicted using the Kirchhoff formula or acoustic analogy, which were developed for aero-acoustics (Lighthill, 1952; Ffowcs Williams and Hawkings, 1969; Wang et al., 2006). The acoustic analogy method has an advantage over the Kirchhoff formula due to its representation of noise in three source terms to which physical

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meanings can be assigned: thickness noise, loading noise and quadrupole noise (Ffowcs Williams and Hawkings, 1969). Meanwhile, regarding far-field radiation noise, in order to reduce computational cost the turbulence-induced quadrupole noise term has usually been neglected. However, unlike the circumstances in air, it has recently been found that turbulence-induced quadrupole noise is also important for understanding the overall characteristics of far-field noise underwater (Ianniello et al., 2014b).

Pressure perturbations of the turbulence-induced noise can be predicted correctly using the Direct Numerical Simulation (DNS) method. However, it is almost impossible to use because of extremely high computational cost (Singer and Lockard, 2002; Inoue and Hatakeyama, 2002). Therefore, to reduce computational expense hybrid methods utilizing Cmputational Fuid Dynamics (CFD) with turbulent models and acoustic analogy methods introduced by Lighthill being actively studied (Wang et al., 2006). Based on Lighthill's analogy (Lighthill, 1952), Curle (1955) has improved the theory to consider a stationary boundary and Ffowcs Williams and Hawkings, (1969) have further developed the method to consider an object moving in arbitrary motion— the Ffowcs Williams–Hawkings (FW–H) analogy. The FW–H analogy was manipulated for computation as formulations 1 and 1A and further refined by Farassat (2007). For practical applications, formulation 1A is commonly used with neglect of the quadrupole noise source term (Wang et al., 2006; Farassat, 2007; Ansys, 2009).

The effort to calculate quadrupole noise has mainly focused on helicopter rotors in the supersonic region due to the associated dominance of quadrupole noise as formulation Q1A (Hanson and Fink, 1979; Farassat, 1987; Brentner, 1996; Brentner and Holland, 1997; Ianniello, 1998). However, while formulation Q1A includes a quadrupole noise term similar to that of formulation 1A that was to be introduced more than two decades later, the method is still underdeveloped and under researched, without ever having been studied for underwater circumstances (Di Francescantonio, 1997; Lockard and Casper, 2005).

In previous work, attempt to forcibly select permeable surface as wall surface condition for formulation 1A to see the effect of including quadrupole noise has been done using commercial software, Ansys FLUENT (Choi et al., 2015). The results was somehow meaningful yet, had no clear physical explanations of increase in sound pressure level using permeable surface. Also, unlike the cases in air, the proper results could only be obtained using reversed normal for underwater cases.

In this study, the use of a Large Eddy Simulation (LES) turbulence model of CFD and developed formulation of permeable FW–H method, which accommodates permeable surface, is shown to predict turbulence-induced noise without neglect of the quadrupole noise source terms. The developed solver, termed Ship NOise Field Operation And Manipulation (SNOFOAM), is based on the OpenFOAM platform, an object-oriented, open source CFD tool-kit (Jasak, 2009; Weller et al., 1998). SNOFOAM can be used as standard solver during the CFD calculation as well as for post-processing protocols to suit research objectives. For simplicity, noise around a circular cylinder is examined using two different methods: the commonly used FW–H method without a quadrupole noise source versus the developed formulation of permeable FW–H method that can take quadrupole noise sources into account.

2. Theoretical background

2.1. Governing equations and subgrid-scale modelling

Large eddy simulations are implemented in this research—for turbulence closure and to lend accuracy comparable to that of acoustic calculations (Wang et al., 2006; Batten et al., 2007). The use of LES to obtain noise predictions by integral solutions of the wave equation has been already used successfully in many previous works, for the high-Reynolds number range in the subcritical regime (Boudet et al., 2003; Takaishi et al., 2007; Kato et al., 2007). In the LES model, the large-scale motions are explicitly computed and for the system to be closed eddies within the scales of low-pass spatial filtering of the turbulent motions are modeled with subgrid-scale modelling (Sagaut, 2006).

The eddy-viscosity assumption is commonly used to model the Subgrid-Scale (SGS) tensor, $\tau_{ij} = \widetilde{u_i u_j} - \widetilde{u}_i \widetilde{u}_j$ in LES, for simplicity, as was begun by Smagorinsky (Pope, 2000; Sagaut, 2006). Here, $\widetilde{u}_i$ is the resolved velocity component in Cartesian coordinates ($i,j \in [1,2,3]$). The Smagorinsky model is based on the Boussinesq approximation, which represents the turbulence stresses as having linear behavior as represented by the large-scale strain rate tensor S_{ij} (implicit summation rule for repeated indices is used and the tilde denotes the filtering operation)

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = -2\upsilon_{sgs}\widetilde{S}_{ij} = -\upsilon_{sgs}\left(\frac{\partial \widetilde{u}_i}{\partial x_j} + \frac{\partial \widetilde{u}_j}{\partial x_i}\right) \tag{1}$$

where δ_{ij} denotes the Kronecker delta and υ_{sgs} is the subgrid-scale eddy viscosity. S_{ij} is rate-of-strain tensor.

The SGS eddy viscosity, by a simple dimensional analysis, can be written as

$$\upsilon_{sgs} = l^2\left|\widetilde{S}_{ij}\right| = l^2\sqrt{2\widetilde{S}_{ij}\widetilde{S}_{ij}} \tag{2}$$

$$l = C_s\widetilde{\Delta} = C_s(\Delta x\Delta y\Delta z)^{1/3} \tag{3}$$

where C_s is a constant and Δ is the filter width (the subgrid characteristic length-scale, the cell size in practice) and l is a differential operator associated with the model for the resolved velocity field. The value of the constant C_s is flow-dependent and found to vary from 0.065 to 0.25 and it is set to be $C_s = 0.2$ (Zhang et al., 2015). The filter width Δ is correlated to the typical grid spacing through the cube root of the cell volume.